Sub-50 attosecond pulse generation from multicycle nonlinear chirped pulses

Yang Xiang,[1,2] **Yueping Niu,**[1,*] **Yihong Qi,**[1] **and Shangqing Gong** [1,†]

[1] *State Key Laboratory of High Field Laser Physics, Shanghai Institute of Optics and Fine Mechanics, Chinese Academy of Science, Shanghai 201800, China*

[2] *College of Computer Science and Technology, Henan Polytechnic University, Jiaozuo 454000, China*

Corresponding author: * *niuyp@siom.ac.cn,* † *sqgong@siom.ac.cn*

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We present a method of producing single attosecond pulses by high order harmonic generation with multi-cycle nonlinear chirped driver laser pulses. The symmetry of the laser field in several optical cycles near the pulse center is dramatically broken, and then the photons which cover a much broad spectrum burst almost only in one optical cycle. So an ultra-broad continuum spectrum appears in the high order harmonic spectrum, from which an isolated sub-50 attosecond pulse could be obtained. The results are almost independent of the length and chirp form of the driver laser pulse.

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The creation of attosecond(as) pulses has opened the door to the new field which is called attosecond science. Attosecond pulses are of great importance for studying and controlling the coherent dynamics of electrons on their natural time scales. So far, attosecond pulses are mainly obtained from the high harmonic generation (HHG) process[1−7]. By selecting many harmonics in the plateau which only contains odd harmonics of the laser frequency, one can obtain an attosecond train. This was observed by Paul *at al* in experiments for the case of multicycle driver pulses[1]. Single attosecond pulse can be generated from the continuous spectrum near the cutoff of the HHG from few-cycle laser pulse. Up to now, the shortest pulse duration achieved by this means is about 80 attoseconds[2]. While the pulse duration used in experiment is shorter than 5 fs, which is so stringent that it can be achieved only by means of state-of-the-art laser technology. So, the single attosecond obtained from multicycle laser pulses attracts great interests. Several schemes have been proposed for the generation of single attosecond in multicycle-driver regime, such as polarization gating technique[3], two-color control[4] and waveform control[5]. While the durations of the pulses obtained by these methods are about several hundred attoseconds, though Hong *et al* pointed out that a sub-100 isolated attosecond pulse could be obtained by two-color control[6], the duration of the laser pulse (800nm) used is 10 fs, which is still shorter than the typical performance of standard laser system ($>$ 25 fs)[3].

In this Letter, we propose an approach to achieve a single attosecond pulse from nonlinear chirped multicycle driving pulses. The prominent advantage of this approach is that the duration of the pulse is less than 50 attoseconds, which is much shorter than that obtained from the other method in multicycle-driver regime, and the result is almost independent of the duration of the laser pulse and the chirp form. The physical mechanism of the single attosecond generation is connected with the well-known semi-classical three step model[8] (TSM): first, the electron tunnels through the barrier formed by the Coulomb potential and the laser field; next, it oscillates almost freely in the laser field; finally, it may return back and recombine with the parent ion at later time. During the recombination, a photon is emitted. Usually, all of this occurs in every half-cycle which may cause the generation of attosecond pulse train. If the electron has few collisions with the nuclear, then the HHG spectrum become continuous, from which a single attosecond pulse can be obtained[9]. In the following, we first use a classical calculation based on the TSM to explore the physical origin of the single attosecond pulse genration. Afterwards, we perform a quantum mechanical simulation using a one-dimensional helium atom model to compare with the traditional method, by solving the time-dependent Schrödinger equation(TDSE). Then we explore the impact of the duration and chirp form on the generation of single attosecond pulse. At last, the conclusion is given.

At first, we consider the classical motion of an electron in a linearly polarized chirped multicycle laser pulse, which has a form of [the atom units (a.u.) are used in all equations in this paper, unless otherwise mentioned.]:

$$E(t) = F \sin^2\left(\frac{\pi t}{\tau} + \frac{\pi}{2}\right) \cos\left[\omega t + \delta(t)\right], \qquad (1)$$

where F, ω and τ is the amplitude, frequency and the pulse length of the laser field. The time-dependent carrier envelop phase (CEP) is set to be[10]:

$$\delta(t) = -\beta \tanh\left(\frac{t - t_0}{\sigma}\right). \qquad (2)$$

The parameters β, t_0 and σ are used to control the chirp form. Such a time-varying CEP can be achieved by means of the comb laser technology[10−12]. In our calculations, F is 0.12 a.u. (corresponds to intensity $I=$

5.0×10^{14} W/cm^2)and ω is 0.057 a.u. (corresponds to wavelength λ=800 nm). The chirp parameters are as follows: β=8.0, σ=200 a.u. and $t_0=\sigma/4.0$. According to the TSM, the return energy of the electron can be obtained by solving the Newton equation dv/dt=-$E(t)$, where v represents the velocity of the electron. The return energies of the electron are shown in Fig.1, as well as the time evolution of the chirped laser pulse whose length is 60 optical cycles (O.C.)[the full width at half maximum (FWHM) is about 58 fs]. From the return energy map, we can see that the max return energy extends to about $30\,U_p$, which is much larger than the well known value $3.17\,U_p$[13], where $U_p = F/(4\omega^2)$, is the ponderomotive energy in the laser field. This is due to the great asymmetry of the laser field near the pulse center, which is discussed in detail in our previous work[14]. Moreover, the electrons with energy larger than about $11\,U_p$ only return within less than 1 O.C., as shown in Fig.1(b). This means that the photons which cover a much broad spectrum burst only in less than 1 O.C., so there should be a much broad continuum spectrum in the HHG, from which a single attosecond pulse could be obtained.

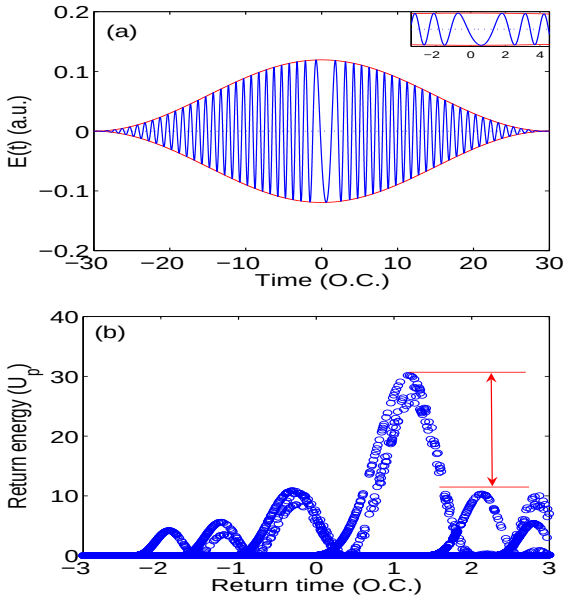

Fig. 1. (Color online) (a) The time evolution of the chirped laser pulse and its envelope. The inset window is the enlargement electric field near the center of the pulse. (b) Classical return energy map.

In order to verify the classical analysis above, we perform a simulation of high harmonic attosecond pulse generation by solving the TDSE. Our model system is a one-dimensional helium atom with a single active electron[15] and dipole approximation. The method for solving the one-dimensional TDSE is split-operator method[16,17]. Once the wavefunction is obtained, the HHG spectrum can be obtained by taking the Fourier transform of the dipole acceleration, applying the Ehrenfest's theroem[18]. The HHG spectrum for the laser field in Fig.1(a) is shown in Fig.2(red solid line). We can see that the HHG spectrum exhibits two plateaus: the cutoff of the first one is about at the 230th order harmonic, corresponding to the energy I_p+11 U_p, where I_p(=24.6 eV) is the ionization potential of helium, and the cutoff of the second plateau is about at the 594th order harmonic, corresponding to the energy I_p+30 U_p. Compared with the return energy map of Fig.1(b), the result obtained from quantum theory is quite in agreement with that from the classical method.

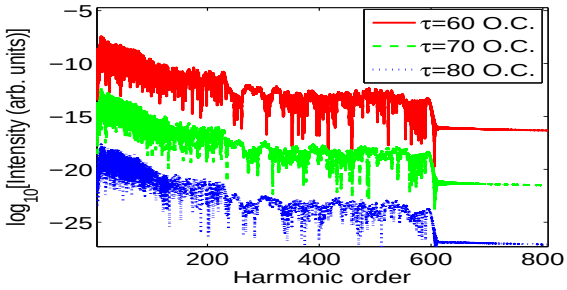

Fig. 2. (Color online) The HHG spectrums of the chirped laser pulses with different lengths. For clarity, the curves have been offset along the vertical axis.

Now we consider the attosecond pulse generation from the second plateau of the HHG in Fig.2(red solid line). Due to the phase mismatch, it is not suitable to select all the continuum spectrum of the second plateau to synthesize single attosecond pulse. So we impose a bandpass with bandwith of 90 order harmonics on the continuum spectrum and make an inverse Fourier transformation, and then an isolated 30 attoseconds pulse is obtained, as shown in Fig.3(red line). In addition, we investigate the attosecond generation from the laser pulses with different lengths. The HHG spectrums for the pulse whose lengths are 70 O.C. and 80 O.C. are shown in Fig.2. As displayed in this figure, though the pulse length varies from 60 O.C. to 80 O.C., the HHG spectrum does not has essential changes. All of the HHG spectrums have two plateaus and the same cutoffs. This is easy to be understand from the laser field in Fig.1(a). It is clear that the symmetry near the center of the pulse is dramatically broken, while has not apparent changes in the rest part of the laser field. That is to say, this type of nonlinear chirp only cause the asymmetry of laser field near the center. Thus, for multicycle pulses, the asymmetry has little differences when the pulse length varies. So the HHG spectrum is almost independent of the pulse length. The sub-50 attosceond pulses generated from the HHG spectrums are shown in Fig.3, and the durations of these pulses have not much difference, just as we expected.

From the classical analysis above, the single attosecond generation should not be much sensitive to the form of the chirp, if such apparent asymmetry as displayed in Fig.1(a) can be obtained. To verify this, we consider the

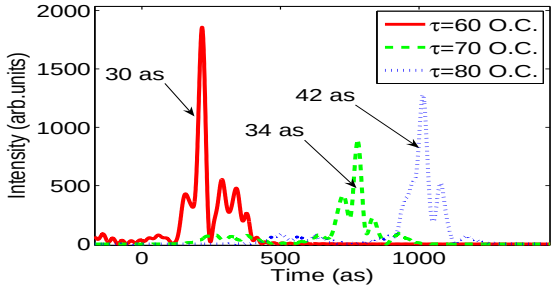

Fig. 3. (Color online) The temporal profiles of the attosecond pulses generated from the HHG spectums of Fig.2. The harmonic orders used are all from the 275th to the 365th.

other form of nonlinear chirps as:

$$\delta_1(t) = -8.0 \arctan(\frac{t-50}{200}), \tag{3}$$

or

$$\delta_2(t) = -\frac{0.04t}{\sqrt{1+0.000015t^2}}, \tag{4}$$

which also could be achieved by means of the comb laser technology[11,12]. The HHG spectrums for the two different nonlinear chirped laser pulses are shown in Fig.4. Both the lengths of the two pulses are 60 O.C.. From Fig.4, we can see that though the forms of the chirps are quite different, the HHG are very similar: both of them have two plateaus and the cutoffs energy are almost the same. For comparison, the same order harmonics are used to generate attosecond pulse, as shown in Fig.5. Clearly, the durations of the pulses are below 50 attoseconds.

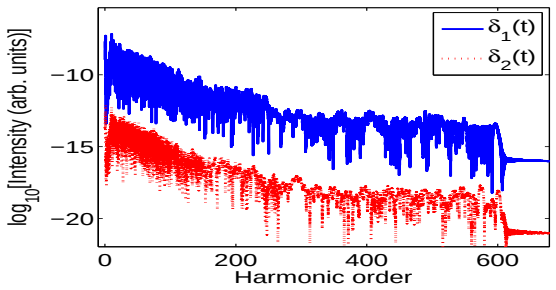

Fig. 4. (Color online) The HHG spectra for the laser pulses with different chirp. For clarity, the curves have been offset along the vertical axis.

In conclusion, we proposed a method of using nonlinear chirp pulses to generate a single attosecond pulse with duration less than 50 attoseconds in multicycle-driver regime. The results are almost independent of the length and chirp form of the driver laser pulse, which may make it easy to be realized in the present experiment condition.

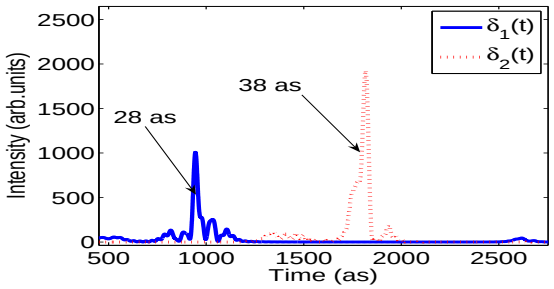

Fig. 5. (Color online) The temporal profiles of the attosecond pulses generated from the HHG spectra of Fig.4. The harmonic orders used are both from the 275th to the 365th.

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